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Chad D. Bowers
Creative Thermal Solutions

Scott S. Wujek
University of Illinois at Urbana-Champaign

Predrag S. Hrnjak
University of Illinois at Urbana-Champaign

Quantification of Refrigerant Distribution and Effectiveness in Microchannel Heat Exchangers Using Infrared Thermography

Chad D. BOWERS*[1], Scott S. WUJEK[2], Predrag S. HRNJAK[1,2]

[1]Creative Thermal Solutions,
Urbana, Illinois, USA
chad.bowers@creativethermalsolutions.com

[2]University of Illinois at Urbana-Champaign, Mechanical Science and Engineering,
Urbana, Illinois, USA
swujek@illinois.edu
pega@illinois.edu

ABSTRACT

Microchannel heat exchangers, specifically evaporators, are known to be susceptible to maldistribution of both the refrigerant and air streams. This maldistribution leads to reduced heat transfer effectiveness of the heat exchanger and thus lower system efficiency and capacity. Besides these reductions in performance, maldistribution in evaporators can also lead to liquid slugging of the compressor. Quantifying the refrigerant distribution using a single parameter in a non-invasive manner for an operable system is difficult and expensive. It is desirable to use a non-dimensional rating parameter that can be applied over a wide variety of heat exchangers: evaporators, gas-coolers, condensers, geometries, and slab configurations. This paper outlines a statistical methodology for quantifying in such a way both the refrigerant distribution and the effective use of heat transfer area using infrared thermography. The parameter was developed to rate heat exchanger distribution on a scale from zero to one; zero being the highest degree of maldistribution and one being uniform distribution. This method also has the advantage of being both non-invasive and low cost.

1. INTRODUCTION

Maldistribution in manifolds providing fluid to parallel flow heat exchangers is a complicated problem that, while greatly studied, is still little understood. Keller (1949), in one of the earlier studies of this very problem, endeavored to improve the distribution in a heat exchanger for compressed air by examining the placement of the exit from the discharge manifold with respect to the inlet. In recent years, the study of manifolds supplying two-phase flow to heat exchangers has become more important as microchannel technology becomes more popular. A large body of literature has emerged over the last decade. Yoo *et al.* (2002) experimentally studied the distribution of an air-water mixture among15 parallel microchannels through a manifold with a rectangular cross section. Cho *et al.* (2003) studied the effect of several parameters, inlet quality, header orientation, and flow entrance orientation (in-line, cross, and parallel), on distribution of two-phase R-22 in a microchannel manifold feeding 15 parallel microchannel tubes. Vist and Pettersen (2003 & 2004) conducted distribution experiments using both R134a and CO_2 in a horizontal manifold feeding 10 parallel heat exchanger tubes using counterflowing water jackets as a heat source. Zhang *et al.* (2003) expanded on the work done by Yoo *et al.* (2002) by studying the distribution of R134a in a horizontally oriented manifold feeding 15 parallel microchannels with downward flow. Webb and Chung (2005) studed how two-phase flow distribution in parallel flow heat exchangers was effected by vapor quality, header area, and protrusion effects in a horizontal header feeding 20 microchannels tubes with downward flow. Bowers *et al.* (2006) studied the effect of entrance length, microchannel protrusion, mass flow rate, and quality on distribution of two-phase R134a in a horizontal manifold feeding 15 parallel microchannels with downward flow. In their work on two-phase flow distribution, Kim and Sin (2006) studied the effects of mass flow rate, inlet quality, microchannel protrusion, flow orientation (upward and downward), and outlet direction on an air and water mixture in a horizontal header feeding 30 microchannels. Adding to the work of Cho *et al.* (2003), Cho and Cho (2006) studied the effect of distribution on the cooling capacity of three prototype evaporators with manifolds feeding 41 parallel microchannels. They reduced the maldistribution by adding twice as many circuits; this increased the cooling capacity of the evaporator by 4% to 10%. Hwang *et al.* (2007) conducted distribution experiments in a horizontally oriented header feeding 30 parallel microchannels with upward flowing two-phase R134a. Kim and Han (2008) expanded on the work done by Kim and Sin (2006) in horizontal headers feeding 10 parallel microchannels with a two-phase mixture of air and water. Other studies not explicitly focused on this issue have noted that refrigerant distribution is an important area of study. Elbel and Hrnjak (2004) noted that the separation of the two phases in the inlet header of an evaporator led to maldistribution and reduced thermal performance of the heat exchanger. The absence of correlations for developing two-phase flow in evaporator inlet headers led Kulkarni *et al.* (2004) to believe that the ability to accurately analyze header designs and their influence on refrigerant distribution is limited. To quantify distribution, these studies were conducted in an invasive manner; meaning that additional instrumentation had to be installed into the heat exchanger or system. These direct measurements of distribution were important in understanding the governing parameters of distribution, but when looking at how distribution affects heat exchanger and system performance it would be preferable to have a non-invasive method of quantifying distribution.

2. DEVELOPMENT OF DISTRIBUTION RATING PARAMETER

Traditionally, the use of infrared (IR) thermography to study refrigerant distribution in microchannel evaporators offers a means of qualitatively examining how the refrigerant distributes itself among multiple parallel channels. The left side of Figure 1 is an example infrared image taken during operation of a single slab, single pass, microchannel evaporator. In this particular evaporator, the refrigerant flow enters through the left side of the bottom header, flows upward through the microchannels, and exits at the right side of the top header. Blue represents colder temperatures, and as the color progresses to red the temperature increases. Because the refrigerant (R134a in this case) evaporates at a nearly constant temperature, the region in which the temperature begins to increase represents where the refrigerant becomes superheated. Conversely, the blue region represents a constant temperature occupied by two-phase refrigerant. In the case presented in Figure 1, it can be inferred that most of the liquid refrigerant flows through the right side of the evaporator because this is the region of the heat exchanger which remains at a constant temperature the longest. Observations of this manner are how qualitative results of the refrigerant within an installed heat exchanger are typically made. While qualitative results and trends are important in understanding performance issues, a widely applicable metric to quantify the distribution of the refrigerant within the heat exchanger would provide a means of directly relating distribution and thermal performance.

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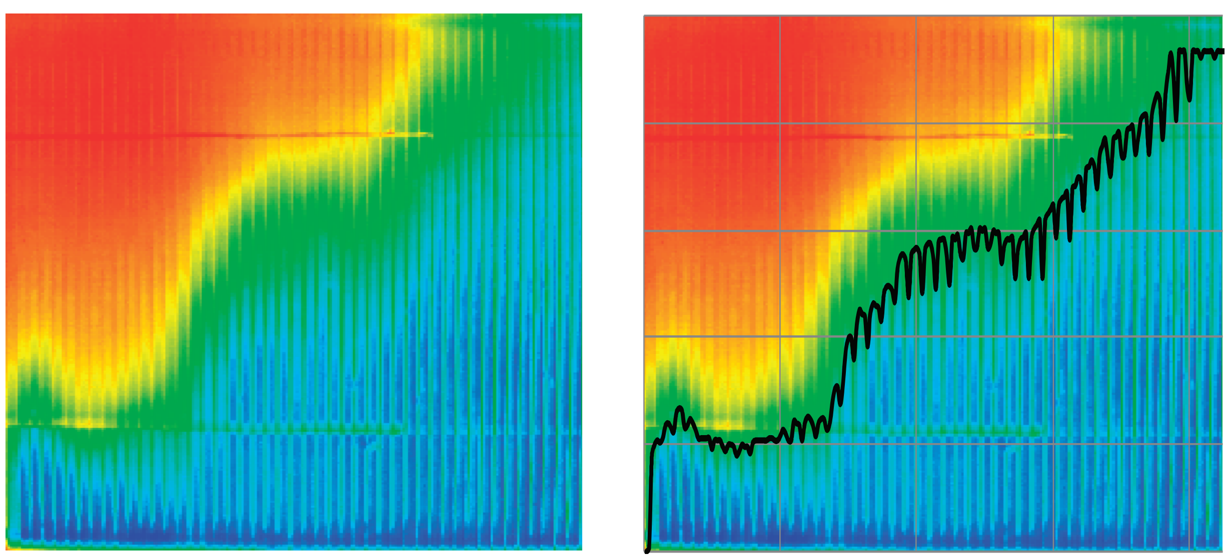

Figure 1: Infrared Image of Evaporator (left) and Infrared Image of Evaporator with the Height H_i Traced along the Width of the Evaporator (right)

In order to describe the development of this metric, referred to as the distribution rating parameter, the infrared image on the left side of Figure 1 will be used as an example. It is important to note is that the infrared camera used in developing this technique was capable of exporting the images in the form of a temperature value matrix or as a color image. The image, or values matrix, is cropped to the size of the heat exchanger. The first step in the analysis is to define an isotherm. The temperature chosen for this isotherm must be such that it is neither higher nor lower than any other temperature experienced within the heat exchanger. For this reason, the isotherm evaluated was set to be the average of the minimum and maximum temperatures, Equation 1. For an evaporator, the temperature of the ambient may be used for T_{max} because the highest temperature that the refrigerant should ever reach in a pinched situation is the ambient. Likewise, the minimum temperature for an evaporator is defined by the evaporation temperature of the refrigerant. Once the temperature T_{iso} has been determined for a given heat exchanger, the image is divided into columns of pixels. For each column i, the number of pixels with temperatures below T_{iso} is determined to define a height (H_i). The average height of all the columns (H_{avg}) is calculated. The image on the right side of Figure 1 contains a plot with H_i overlaid onto the IR image.

$$T_{iso} = \frac{T_{\min} + T_{\max}}{2} \tag{1}$$

Once the heights and the average height are determined, the distribution rating parameter ϕ can be calculated using Equation 2. The variable n is the number of columns in the image. Equation 2 is based upon the coefficient of variation used by Bowers *et al.* (2006) to quantify distribution in a manifold distributing R134a to an array of 15 microchannels. The coefficient of variation equation was adjusted so that the distribution rating parameter falls between 0 and 1; where 0 represents the highest degree of maldistribution and 1 represents completely uniform distribution. In addition to modifying the range of the coefficient of variation, heights determined by temperatures were evaluated instead of the mass flow rates which were used by Bowers *et al.* to express distribution. One advantage of formulating the rating parameter in this way is that it can be applied to evaporators with a variety of sizes and shapes to compare how distribution is affected by different geometries compares. The other advantage is that the bounds of the parameter (0 and 1) correspond to realistic limiting distribution cases. In the case of the IR image shown in Figure 1, the distribution rating parameter was determined to be 0.75.

$$\phi = 1 - \frac{\sum_{i=1}^{n} \left| H_i - H_{avg} \right|}{2nH_{avg}} \tag{2}$$

To understand how the distribution rating parameter relates to IR photographs, three theoretical examples of distribution and resulting distribution rating parameters are shown in Figure 2. The example on the left represents the extreme case in which only one microchannel in an entire evaporator receives liquid and the rest receive superheated vapor at the ambient temperature. In this case only one microchannel is available to perform any cooling. When the distribution rating parameter is applied to this case, the value approaches zero as the number of columns increases. The example in the middle of Figure 2 represents the case in which half of the evaporator receives liquid that does not become superheated and the other half only receives vapor at the ambient temperature. In this case, the distribution rating parameter is 0.5. A case in which liquid refrigerant is evenly distributed equally to all channels is illustrated on the right side of Figure 2. This is the ideal case from a distribution point of view, resulting in a distribution rating parameter of 1. If no superheat appears in the coil, the distribution rating parameter will also return a value of 1, this is reasonable because in this case there is no temperature maldistribution, or hot spots, which typically occur in cases when the refrigerant is maldistributed.

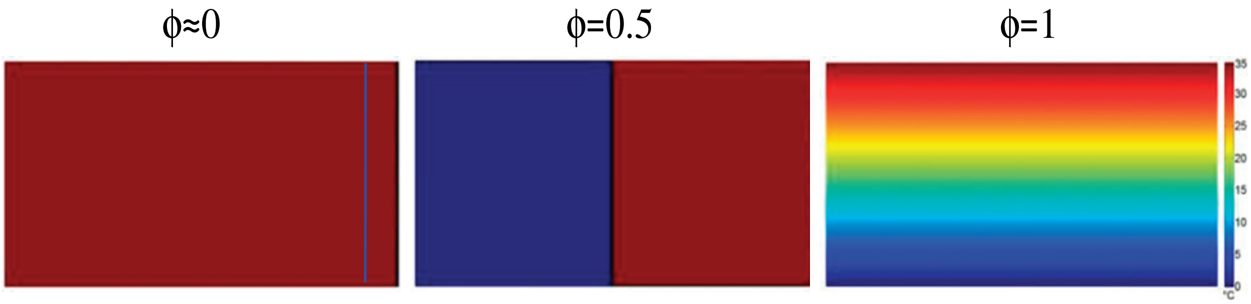

Figure 2: Three Theoretical Examples of Refrigerant Distribution with Corresponding Distribution Rating Parameters

3. EXPANDING DISTRIBUTION RATING PARAMETER TO OTHER DESIGNS

3.1 Using the distribution rating parameter when microchannels have a horizontal orientation

While the distribution rating parameter was developed to rate the refrigerant distribution in microchannel evaporators with the microchannels oriented vertically, some applications use evaporators with horizontally oriented microchannels. For such cases, a simple method of modifying the distribution rating parameter was developed. The isotherm defined by Equation 1 remains the same, however the length of the number of pixels to the left of the isotherm L_i in each row of the image is now of interest. These modifications are illustrated in Figure 3 and Equation 4. If the same IR image shown in Figure 1 is rotated 90˚, and the length of the pixels with temperatures lower than the isotherm examined, the same distribution rating parameter would be calculated.

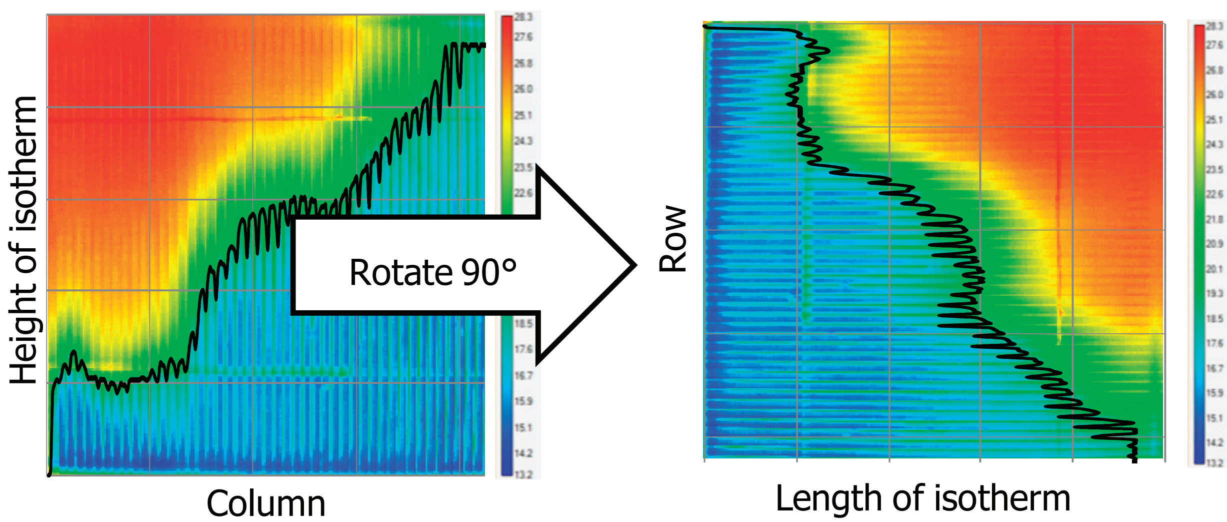

Figure 3: Evaluating Evaporators with Horizontal Channels instead of Vertical Channels

$$\phi = 1 - \frac{\sum_{i=1}^{n} \left| L_i - L_{avg} \right|}{2nL_{avg}} \quad (4)$$

3.2 Using the distribution rating parameter for multiple circuit designs

Another modification to been made to allow the determination of the parameter for use with single slab evaporators with more than one circuit. An example infrared image of such an evaporator is shown in Figure 4. In this example, the refrigerant inlet is at the top left of the heat exchanger. Refrigerant flows down through Circuit A into an intermediate header before flowing up and out through Circuit B, where it exits the evaporator at the top right. Two possible approaches could be considered when evaluating an evaporator such as this, with multiple circuits. The first approach is to evaluate the entire heat exchanger as if there is no knowledge of the circuiting. If this approach is applied to the image in Figure 4, a distribution rating parameter of 0.91 is determined. This is a valid approach that lends itself well to comparing heat exchangers of different geometry and circuiting; however, it does not describe the distribution within each circuit.

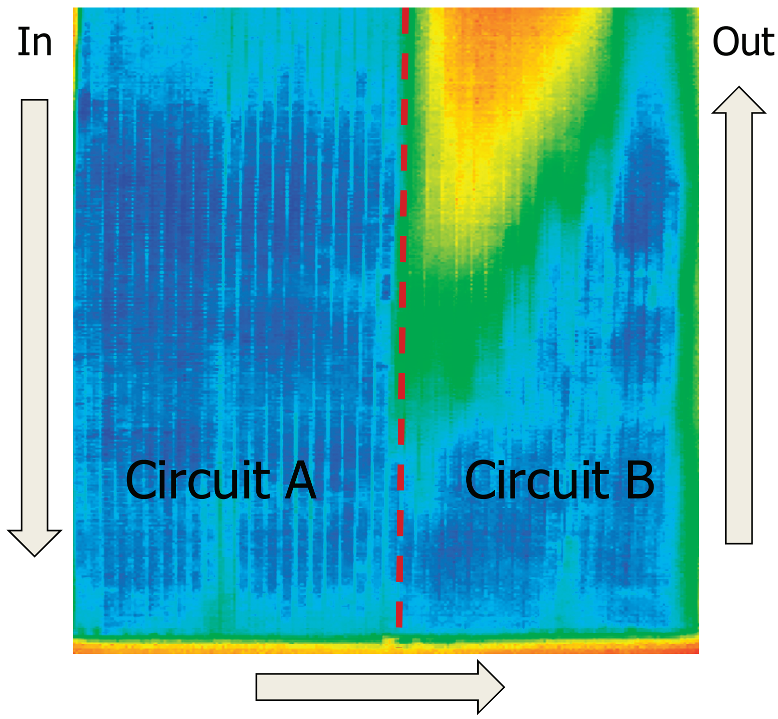

Figure 4: Infrared Image of a Single Slab Evaporator with Multiple Circuits

The second approach is to analyze each circuit independently and determine a distribution rating parameter for each. Using the example of Figure 4, Circuit A has a distribution rating parameter of 1 because there is no superheat within this particular circuit. It should be noted that this does not necessarily mean that the liquid is evenly distributed within Circuit A, but that if there is refrigerant maldistribution within this circuit, it is not “seen” by the air. Clearly, more liquid refrigerant flow in Circuit B is on the right side of the circuit than on the left, the two phase region occupies a large portion of the area causing Circuit B to receive a distribution rating parameter of 0.89.

4. EXAMPLES OF DISTRIBUTION RATING PARAMETER APPLIED TO FUNCTIONING MICROCHANNEL EVAPORATORS

As a part of the development of the distribution rating parameter it has been applied to a variety of microchannel designs in various distribution studies. In the following section, examples of the distribution rating parameter applied to two evaporators installed in an automotive air-conditioning system will be given. The first example, Evaporator A, is a microchannel evaporator with vertically oriented microchannels, having a single slab, single pass design. The refrigerant flow enters the evaporator at the bottom left and exits at the top right. IR images of Evaporator A under three different operating conditions are shown in Figure 5, with the corresponding distribution rating parameters. In Condition 1, the refrigerant distribution is very similar to what other researchers have observed in horizontal microchannel headers with upward flow. Namely, that the majority of the liquid flows through the microchannels at the opposite end of the header from the inlet. The distribution rating parameter for

Condition 1 was determined to be 0.72. In the case of Condition 2, it appears that slightly more liquid may be flowing through the left part of the evaporator. This slight change results in a minor improvement of the distribution rating parameter from 0.72 to 0.76. In Condition 3, the refrigerant distribution within Evaporator A has improved greatly from Condition 1. While the right side of the evaporator still seems to be receiving more liquid flow than the left side, the flow on the left side of the heat exchanger appears much more uniform than in Conditions 1 and 2. The distribution rating parameter reflects this apparent improvement in distribution by increasing to a value of 0.85.

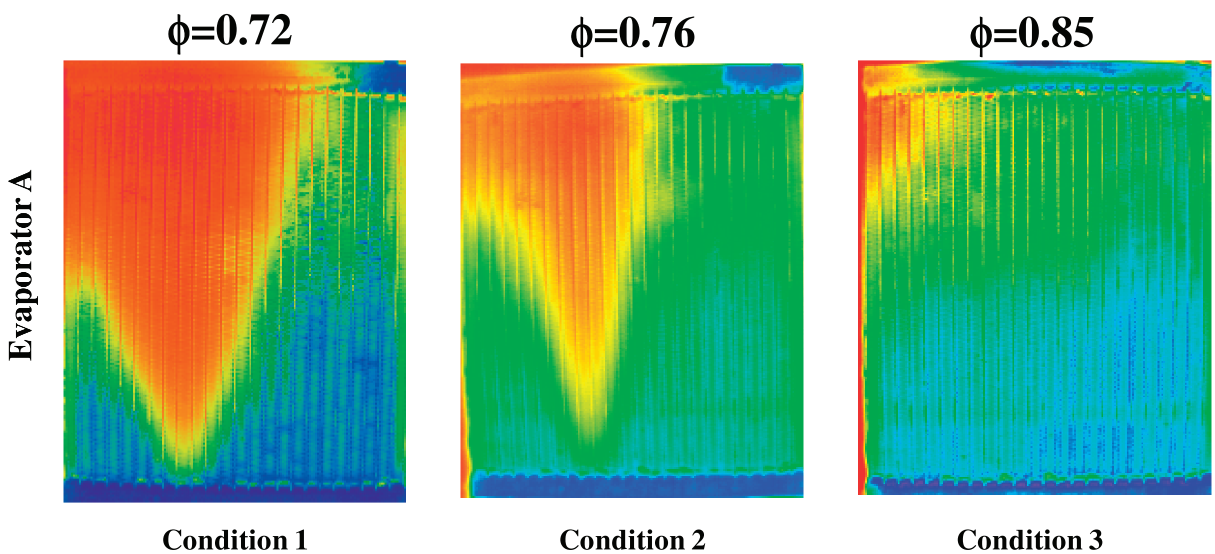

Figure 5: Examples of Infrared Images and Distribution Rating Parameter for Three Conditions in Evaporator A

A set of distribution rating parameter examples applied to an installed evaporator are shown in Figure 6. In this case, the microchannel heat exchanger, Evaporator B, has refrigerant entering from the top right and exiting

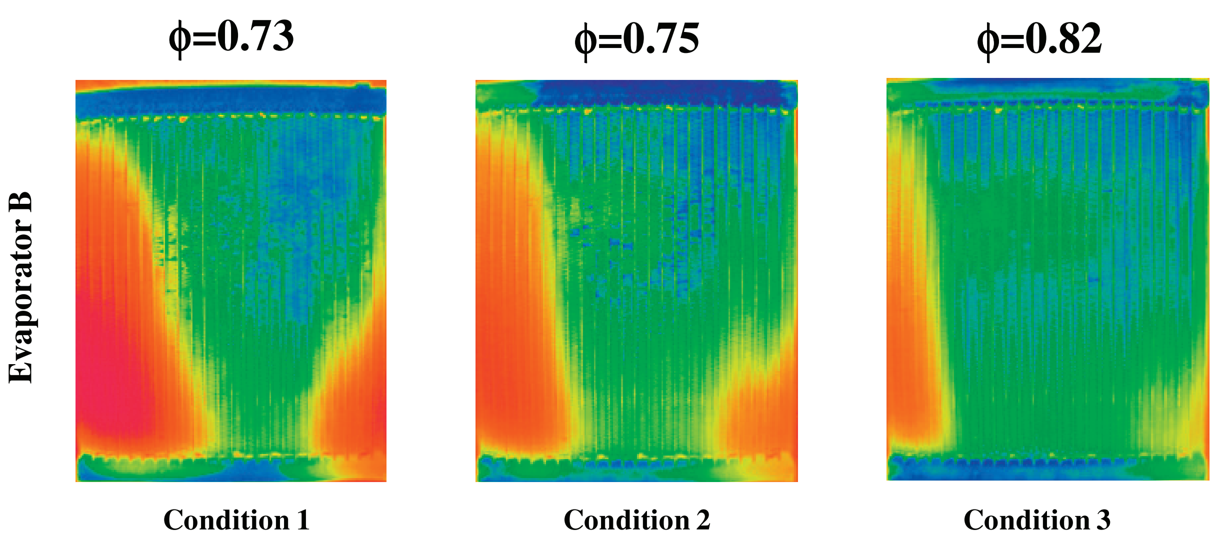

Figure 6: Examples of Infrared Images and Distribution Rating Parameter for Three Conditions in Evaporator B

at the bottom left. Again, three different conditions are presented. The general trends seen in the IR images correspond well to what would typically be expected in an evaporator of this configuration. Namely, when the flow enters from the top, the microchannels closer to the inlet are preferentially fed with liquid and the microchannels furthest from the inlet see little or no liquid flow. In Condition 1, the distribution rating parameter is determined to be 0.73. Again, by comparing Conditions 1 through 3 for Evaporator B, as the distribution qualitatively appears to improve, the distribution rating parameter shows a corresponding improvement. A very interesting comparison of Condition 1 in Evaporators A and B can be made: the refrigerant distribution appears very different in these cases, but the distribution rating parameter rates are very similar. This serves to underline how the rating parameter can be used to make a quantitative comparison of distributions that qualitatively appear very different.

5. CONCLUSIONS

Distribution of the refrigerant within microchannel heat exchangers is one of the important issues needing to be well understood for good design and implementation of microchannel technology. To that end, many researchers have focused on quantifying distribution and its governing variables through mass flow measurements. These measurements tend to be invasive and limit the ability to study how refrigerant distribution in heat exchangers affects both heat exchanger and system performance. A distribution rating parameter has been developed to quantify the refrigerant distribution in microchannel heat exchangers as well as the effective use of the available heat transfer area through the use of infrared thermography. This parameter rates refrigerant distribution within a heat exchanger on a scale from zero to one; zero being the highest degree of maldistribution and one being uniform distribution. While developed for use with microchannel evaporators with vertical channels, it has been shown that this parameter can be expanded to capture various other heat exchanger orientations and circuiting. The range of applicability allows comparison of the refrigerant distribution in different designs of microchannel heat exchangers. This method also has the advantage of being both non-invasive and low cost

NOMENCLATURE

H	Height	(Pixels)
L	Length	(Pixels)
n	Number of rows or columns	(–)
T	Temperature	(°C)
ϕ	Distribution Rating Parameter	(–)
β	Chord Angle	(°)
σ	Standard Deviation	(–)

Subscripts

avg	average
iso	isotherm
max	maximum
min	minimum

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